Aerospace

Landing aircraft under poor conditions

Time-reference scanning beams characterize the all-weather microwave landing system that will replace present systems

Last April, a divisional meeting of the International Civil Aviation Organization (ICAO) settled upon a new all-weather landing system that will eventually replace the present instrument landing system (ILS) for aircraft. The choice of the United States/Australian time-reference scanning-beam microwave landing system (TRSB MLS) ended a selection process that started ten years ago in the U.S., and six years ago in ICAO, that, as the box on page 54 indicates, was not without controversy and debate.

In the most fundamental sense, TRSB MLS is a system approach to the landing-guidance problem—it can meet a wide variety of diverse performance, economic, and safety requirements and still supply a universal airborne receiver-processor able to operate with all ground systems. It must provide for present and future operational needs, such as category I, II, and III landings (200-, 100-, and 0-foot ceilings respectively). And it requires flexible approach paths and precision navigation in the terminal area for noise abatement and more efficient approaches.

A choice of cost and performance levels to meet the needs of diverse users also must be available. Moreover, the system must be able to be installed easily at many sites unable to accept ILS.

MLS can achieve these objectives because of two major factors: the choice of an operating frequency in the microwave C-band (5 GHz), and the design of its signal format. The relatively short wavelengths at C-band permit the design of very narrow scanning beams with antennas of reasonable size that achieve high guidance accuracy in the presence of multipath signals (those that are reflected from airport structures). The directive beams provide freedom from siting effects and allow installation in difficult terrain. The TRSB antennas are small enough that they can be placed in front of ILS antennas without affecting the performance of ILS. That the two systems can "coexist" during the transition period has been demonstrated.

Three features characterize the signal format of the TRSB system. The first is time-division multiplex (TDM), which provides all information in sequence to the airborne receiver (Fig. 1). Second, each guidance function—azimuth, elevation, or others—is self-contained and independent in a time slot in the sequential format. The airborne receiver recognizes each function and processes it independently. Functions can be added or deleted from the ground installation without affecting the operation of the receiver. A third feature of the format is that provisions are made for the transmission of data to supplement the landing-guidance information.

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How TRSB MLS works

The TRSB is an "air derived" system operating in the C-band. Ground-based equipment supplies signals to a receiver in the landing aircraft to determine position information: two angle coordinates and a range coordinate. The angle information is derived by measuring the time difference between the successive passes of highly directive, narrow fan beams. One beam scans in azimuth and one in elevation. The range information is derived from equipment similar to conventional L-band distance-measuring equipment (DME) modified for additional precision.

The TRSB signal format has been defined to provide information at high data rates in sequence for the angle functions of azimuth, elevation, flare, and missed-approach azimuth. The format includes a time slot for 360-degree azimuth guidance with provision for growth of additional functions. The channel plan has 200 channels of 300-kHz bandwidth in the 60 MHz between 5031 and 5091 MHz. Auxiliary data at a high rate give other approach and landing information, such as runway condition and ground-equipment location constants for the computation of automatic landing trajectories. Basic data are available for the minimum-capability receiver, including such information as the minimum acceptable glide path at each facility and the operational status of each subsystem installed.

Basic and auxiliary data are transmitted independently throughout the coverage volume on a broad-sector beam. Such a broad-sector transmission precedes each scanning-beam transmission and is called the "preamble." Its modulation, along with that of the basic and auxiliary data words, is direct differential phase shift keying of the RF carrier.

The output data samples of the airborne receiver, one for each pair of beam scans, can be reconstructed to an analog signal by a simple zero order hold circuit, or they can be inputted directly to digital flight-control systems (FCS). (The scanning beam can be viewed as the sampling element in a sampled-data system, wherein the approach paths are reconstructed from the data samples.)

Narrow fan beams with very low sidelobes are generated by the ground equipment by electronically scanned antennas. This includes phased arrays—which, due to their parallel structure, offer an extremely reliable signal in space. In azimuth, the fan beam scans horizontally and is designed with a sharp lower side cutoff to avoid illumination of the airport surface. In elevation, the

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narrow beams minimize the effect of radiation toward the airport surface, thereby affording accurate guidance to very low angles.

The airborne equipment receives the ground-generated signal (Fig. 1B) and subjects the signal to acquisition criteria before it is accepted. It continues validation after acceptance, so that it will acquire and maintain track of the proper signal in the presence of multipath signals.

The TRSB concept is simple, and is easily visualized for its design, simulation, and validation: a single channel transmitter for each function, a parallel redundant structure that provides continued system operation even with failures of individual array elements, and integral monitoring within the phased array structure for rapid fault location and uninterrupted system operation. Digital techniques generate the scanning beams, monitor the equipment, and process the guidance signals.

The TRSB can operate in severe multipath (signal reflection) environments by resolving "out-of-beam" multipath signals inherently with the narrow ground-generated beams and by minimizing the effect of "in-beam" multipath by the averaging of successive data samples supplied at high rates. In addition, the shape of the nonscan dimension of the antenna radiation patterns is controlled to reduce multipath effects further.

The system can be easily installed and commissioned because of the absence of electronic adjustments in the phased-array antennas and associated equipment. Maintenance is simplified by the use of modules, which, when replaced, require no further calibration to provide continued accurate guidance.

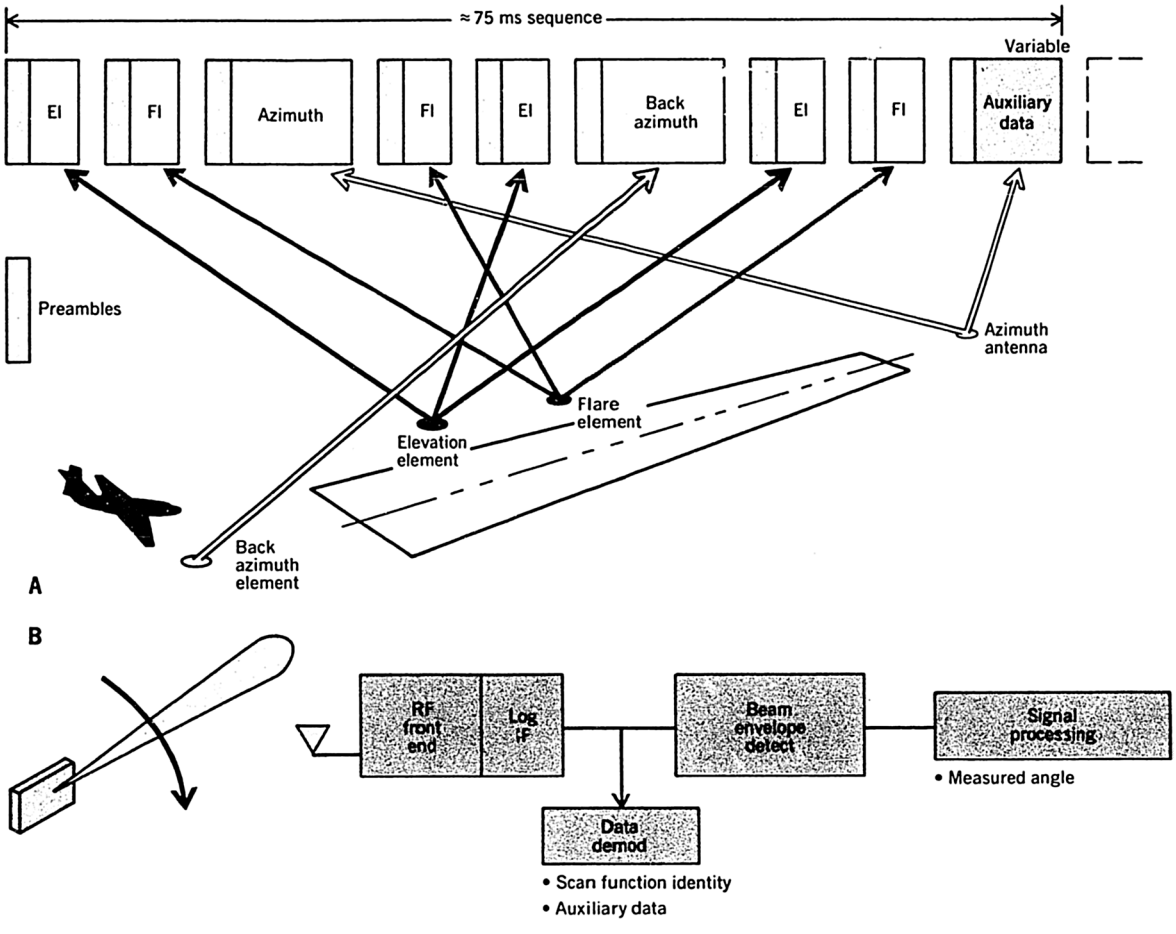
A single field monitor combined with an integral monitor evaluates the accuracy of guidance over the complete angular coverage volume. Both executive and maintenance functions are included. Automatic equipment switchover is provided in systems requiring redundancy. All monitored parameters can be transmitted to remote locations for maintenance planning and scheduling.

Accuracy requirements

Accuracy requirements placed on the wide-angle performance of MLS to execute curved paths are in the process of being defined by the Federal Aviation Administration (FAA), but typically are of the order of a few tenths of a degree. The most stringent requirements, as might be expected, are at the decision heights, at runway threshold, and at touchdown and rollout for category III landings.

One approach to the specification of landing-guidance accuracy is to provide a uniform "autoland" signal quality at threshold independent of the certified category of the landing system. The microwave beams for MLS are inherently capable of providing this accuracy as present systems have demonstrated, and with autoland signal quality at all runways, suitably equipped aircraft can execute autolands as a routine operation.

[1] (A) The MLS scan format, together with the detailed parameters of each time slot, comprise the signal format. (B) The airborne equipment detects in sequence the identity of the angle-guidance function, timing information, angle data, and basic or auxiliary data.

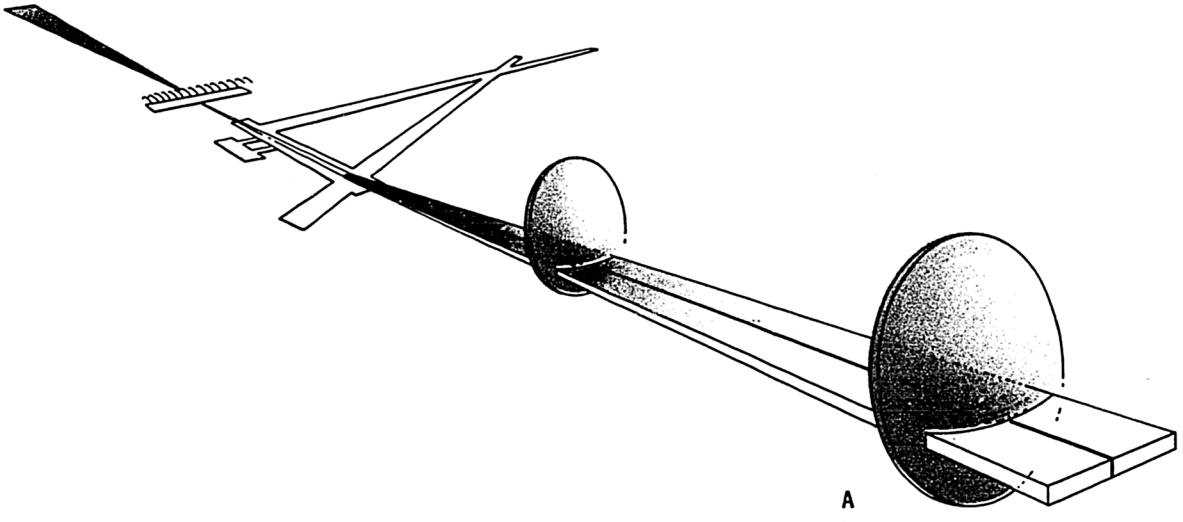


ILS to MLS

Within a few years after man learned to fly, a need was recognized for approach and landing guidance to aid the pilot during periods of restricted visibility. Then, during the 1920s, the growth of aviation, particularly commercial, created a demand for all-weather and night flying. As a result, experimental systems were tested in several countries during the late '20s, leading to the development of the present instrument landing system (ILS).

The first commercial VHF/UHF ILS was demonstrated in 1939 at Indianapolis, Ind. It was adopted for U.S. use in 1941, and by the International Civil Aviation Organization (ICAO) as the international standard in 1949. However, although ILS has served the aviation community well, it restricts arriving aircraft to a single flight path (Fig. A) and has a limited channel capacity, which causes frequency-allocation problems in some areas. Further, it cannot be employed in mountainous sites because of the necessity of relatively flat terrain in front of the antennas to permit proper guidance-beam shaping.

In 1967, the Radio Technical Commission for Aeronautics (RTCA) formed a special committee (SC-117) to explore the feasibility of a universal approach and landing system. The committee's work was aided by over 450 experts, who reviewed the state-of-the-art technology, synthesized operational requirements, developed an overall microwave landing system (MLS) concept and recommended signal format, and produced the now-famous SC-117 report, "A New Guidance System for Approach and Landing," published in December 1970. It was followed in 1971 by the U.S. National Plan, jointly spon-



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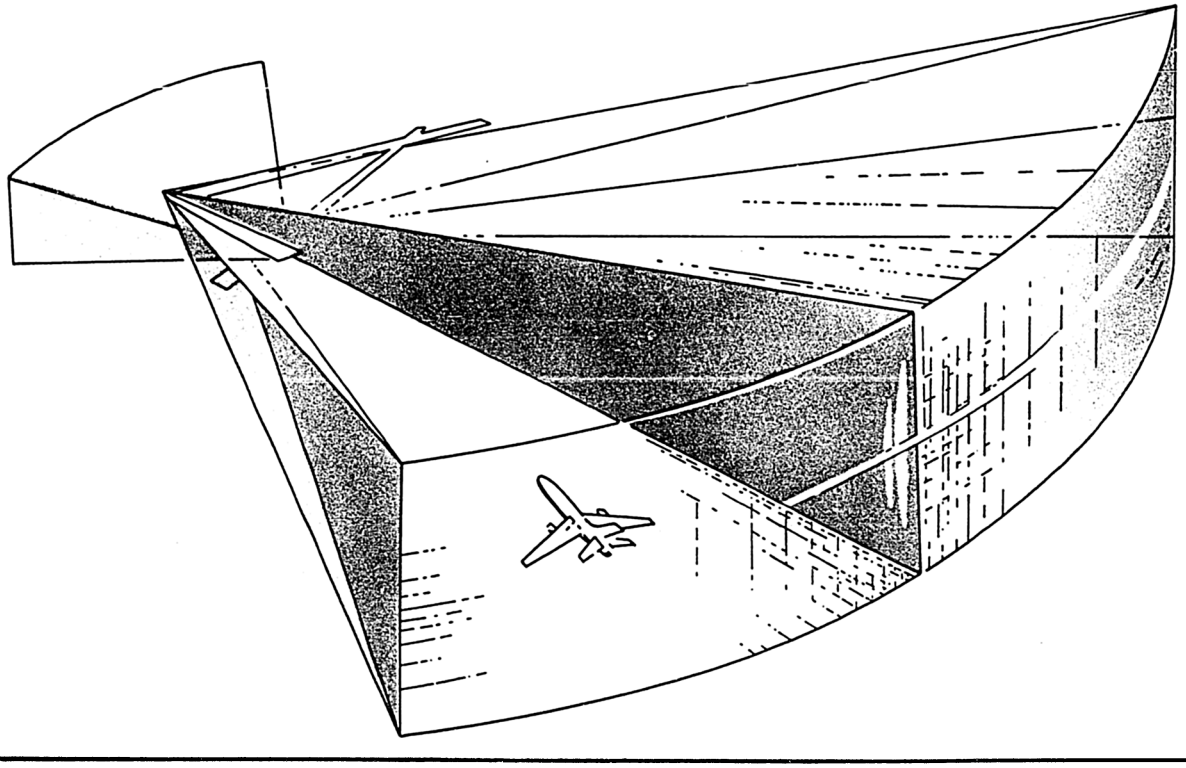


B

sored by the Department of Transportation, the Department of Defense, and the National Aeronautics and Space Administration (NASA). The Federal Aviation Administration (FAA) was designated to lead the program, which was divided into three phases:

Technique analysis and contract definition. Each of six competing contractor teams was required to define a completely integrated system. This effort, completed in late 1972, resulted in a feasibility model demonstration program, test and evaluation criteria, and a prototype system-validation program.

Feasibility demonstration. The field demonstration and testing of feasibility hardware took place at the FAA's National Aviation Facilities Experimental Center (NAFEC) at Atlantic City, N.J., and NASA's Wallops Flight Center in Virginia in 1973 and 1974. Four contractors selected from the first phase ground- and flight-tested their respective systems (ITT and Bendix at NAFEC, and Texas Instruments and Hazeltine at Wallops). Two of the systems employed the conventional scanning-beam technique (Bendix and Texas Instruments); the other two made use of a Doppler scanning technique (ITT and Hazeltine). Intensive evaluation led to the selection of a time-reference scanning-beam (TRSB) approach, with Bendix and Texas Instruments chosen as the contractors for the prototype phase.

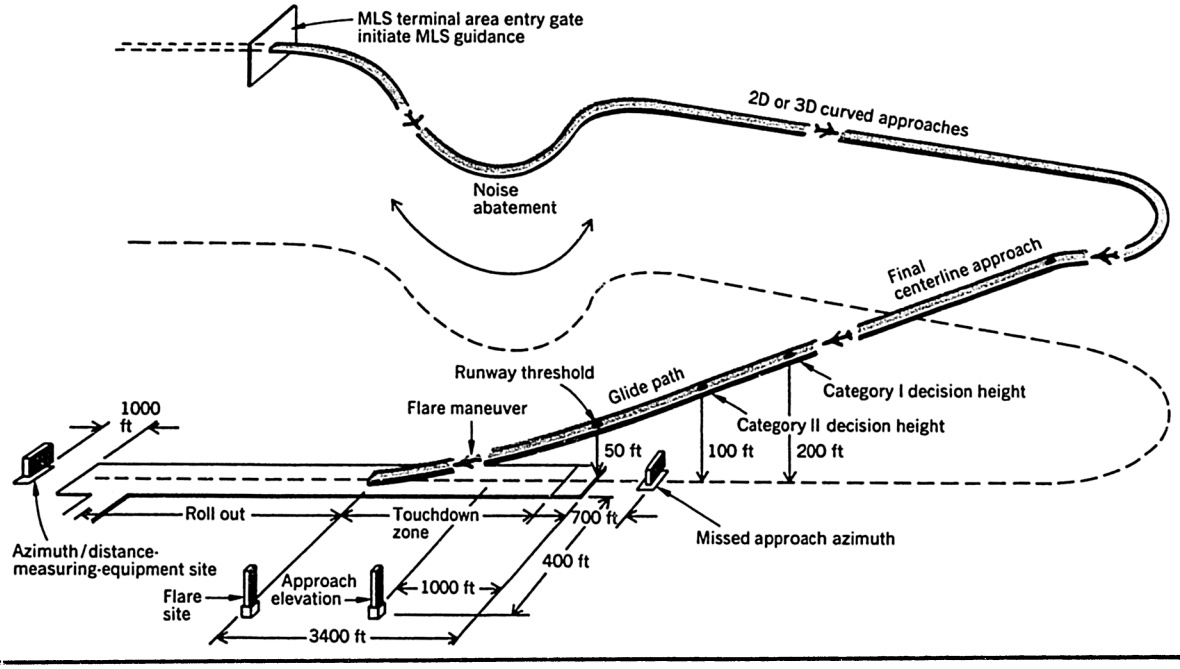
Prototype development and evaluation. Both contractors built two systems designated "small community" and "basic narrow aperture." The small-community system was designed to provide a low-cost landing system for small airports (up to 5000-foot runways); the basic-narrow-aperture system was intended for service at airports with up to 8000-foot runways. The Bendix hardware was delivered in the middle of 1976 and installed at NAFEC for evaluation. Texas Instruments delivered its systems to NAFEC and Crows Landing, Calif. Bendix equipment from feasibility phase formed the primary "test-bed system" to obtain data to be used in writing the U.S. proposal to ICAO for the TRSB MLS technique. The Bendix prototype equipment, in addition to the test bed, was subsequently demonstrated at operational sites worldwide.

ICAO, during the same period, was examining the suitability of MLS for international civil air commerce standardization. Member ICAO states were invited to submit system proposals, and, by late 1975, definitive proposals had been received from the United Kingdom (Doppler), Australia (TRSB), Federal Republic of Germany (a DME-based landing system), France (a ground-derived system), and the U.S. (TRSB). The French proposal was not as complete as others and was subsequently withdrawn.

In March 1977, the TRSB MLS was recommended for international adoption—although the selection process was by no means as smooth as might be implied by this summary. There was considerable debate among the proponents of the Doppler, DLS, and TRSB systems both before and after the recommendation. There was a U.S. Congressional hearing on the "MLS situation" and tests of both the U.K. Doppler system and the U.S. TRSB system were performed throughout the world. However, in the end, the detailed work of ICAO's All Weather Operations Panel remained the principal basis for actual system selection at the April meeting.

[left] The instrument landing system (A) provides a single flight path and operates at VHF/UHF frequencies. Distance from touchdown is provided by marker beacons operating at 75 MHz. Aircraft are required to position along the single flight path at safe separation distances, which are determined by the FAA controller and depend on the size, speed, and mix of arriving aircraft. The time-reference scanning-beam microwave landing system (B) provides a volumetric coverage with up to ±60 degrees in azimuth and from 1 to 20 degrees in elevation. Distance from touchdown is provided by precision distance-measuring equipment. The microwave landing system can be used in difficult mountainous terrain where the instrument landing system cannot be employed.

[below] The landing process consists of curved paths for noise abatement, vertical curved or segmented guidance, and the transition to the final centerline approach. The decision heights where the pilot must be able to "see to land" are 200- and 100-foot ceilings—categories I and II respectively. The flare maneuver, touchdown, and rollout complete the landing. MLS must support each of these maneuvers under "instrument flight rule" conditions. The elevation element, located 1000 feet from threshold and offset from the runway centerline by 400 feet, provides elevation guidance to the decision window in category I and II operations and to threshold in category III (zero ceiling). The approach-azimuth element provides lateral guidance to the decision window in category I and II operations and to touchdown and rollout in category III. The flare maneuver is performed manually for categories I and II by visual reference, but, for category III, positive azimuth and vertical guidance are required to touchdown.



Many factors contribute to the lateral and longitudinal touchdown dispersion for typical landings, including the various wind components, flight-control errors, and MLS guidance errors. The MLS guidance error is the difference between the guidance angle, as indicated by the MLS receiver, and the "true" geometric angle, which is relative to centerline in azimuth or the horizontal in elevation.

The U.S. standard for automatic landings specifies that the aircraft lateral touchdown dispersion should not exceed ±27 feet. The ICAO All Weather Operations Panel allotted approximately half this error (±20 feet) on a root-sum-square basis to the landing-guidance system that ICAO termed "a full-capability system."

For vertical guidance dispersion, ICAO specified ±2 feet for the full-capability system. The flight test data discussed in this article are compared with these full-capability-system accuracy limits.

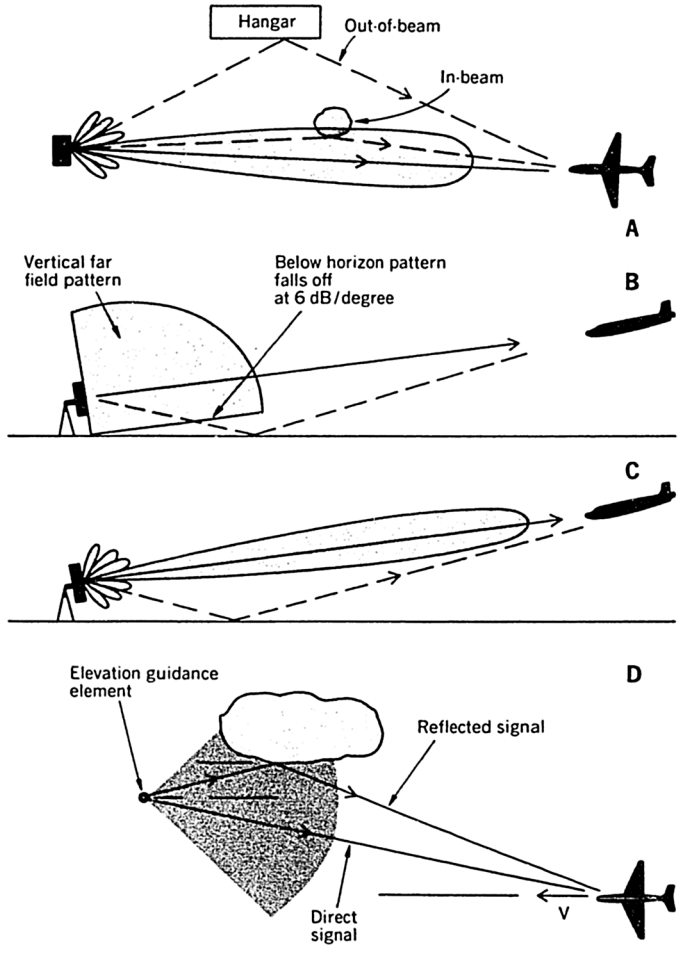
The reflection of guidance signals from airport structures has plagued the traditional instrument landing system from its inception. The ability to operate in the presence of these "multipath" signals is a firm requirement for the MLS, and the system has been designed to provide accurate guidance in these situations.

Two types of multipath signals influence the angular separation of the direct and multipath signals. If the multipath reflector subtends a substantially different angle with respect to the angle subtended by that of the landing aircraft, the two will be received at substantially different times at the aircraft receiver. This situation is termed "out of beam," and the effect of the multipath signal can be removed by placing a time gate in the receiver around the direct signal, thereby rejecting all others.

If, however, the two signals are not separated in angle, they overlap in time and cannot be resolved. For this situation, called "in-beam" multipath, the system is designed to minimize the in-beam multipath component of the signal by antenna-pattern control and to take advantage of motion averaging—which is possible when the error varies rapidly. If the variation is more rapid than that required to provide an adequate update rate, the signal is inherently averaged to reduce the effect of the multipath signal. Motion averaging can be performed in TRSB because a data rate of only 4 or 5 Hz is required; therefore, since the TRSB data rates are higher than these values (13.5 Hz for azimuth and 40 Hz for elevation), the samples are averaged in the receiver output filter.

Methods of avoiding the generation of an in-beam multipath are associated with the design of the antenna patterns shown in Fig. 2. The four cases of potential multipath situations illustrated show how MLS avoids errors and provides accurate guidance for both in-beam and out-of-beam situations.

[2] (A) Lateral multipath in azimuth guidance. Azimuth ground elements produce fan beams, narrow in the horizontal plane or scan direction, and protect the guidance signals from in-beam multipath. TRSB azimuth antenna beam widths are chosen so that, along runway centerline, the multipath from airport structures is always out-of-beam. (B) Azimuth vertical multipath. TRSB azimuth sites are insensitive to ground terrain because they employ "pattern control" to the vertical antenna pattern. This is accomplished through the use of a large, vertical antenna aperture, which allows the design of "far-field" radiation patterns that fall off rapidly below the horizon and limit the energy that would otherwise be reflected from the ground. These radiation patterns will permit accurate signal guidance down to 3 feet above the runway at the end of a very long (15 000-foot) runway. (C) Elevation vertical multipath. The reflections from the ground surface remain out-of-beam as long as the angle between the direct and multipath signals is about twice the beam width of the antenna. (D) Elevation lateral multipath. Elevation ground elements have a narrow beam in the vertical plane, but a wide beam in the azimuthal or horizontal plane. They are susceptible to in-beam reflections from buildings and other obstacles within the coverage zone of the system. Motion averaging as well as lateral pattern shaping will reduce potential errors.



Test and demonstration program

Tests by the FAA of TRSB accuracy and operational capabilities over the past four years have demonstrated that the signal-in-space generated by the ground equipment has the required accuracy over the intended lateral, vertical, and range coverage of the MLS service volume. The tests also demonstrated the ease with which TRSB MLS can be installed at difficult sites. Operational objectives included the capability to fly curved approaches and to perform automatic landings.

The accuracy and coverage tests took place primarily at the FAA's National Aviation Facilities Experimental Center (NAFEC) near Atlantic City, N.J., and at the Naval Auxiliary Landing Field at Crows Landing, Calif. The tests were performed over a coverage volume of ±60 degrees in azimuth, 1 to 20 degrees in elevation, 20 nautical miles in range, and down to 8 feet over the runway in the touchdown zone. A number of flight paths were flown to evaluate this wide-angle coverage volume, including straight-in approaches at various elevation or glideslope angles and azimuth radials.

The concept of the flight test was to view the aircraft as

a probe that sampled the signal-in-space. Its coverage and accuracy performance were determined by recording the airborne receiver system "flags," which raise when inadequate signals are received, and by comparing the MLS angle measurement with a ground reference. Flight-error traces were made by subtracting the position of the probe aircraft as measured by the ground-reference tracker from the position of the aircraft as measured by the MLS angle receiver and distance measuring-equipment avionics. Azimuth- and elevation-error traces taken on a full-capability version of the system are well within the ICAO accuracy limits.

Radial and orbital flights were required to test the signal-in-space throughout the service volume provided by MLS. The constant-altitude radial flights ensure that, for a given azimuth radial, the signal was present and accurate over the specified vertical coverage (elevation angle) and range. Radial flights were flown at altitudes of 2000, 3000, and 10 000 feet from ranges beyond 30 nautical miles. The error trace indicated that the azimuth guidance is well within ICAO limits. Flight-test results also confirmed that power budgets were adequate to provide accurate guidance beyond the ICAO specification of 20 nautical miles.

Orbital tests flown at ranges of 5 and 20 nautical miles and at altitudes of from 2000 to 10 000 feet measured lateral coverage of the elevation and azimuth functions. The tests also verified the power-budget parameters at the coverage limits and ensured that the system out-of-coverage indication feature functioned properly. In a particularly dramatic example of the vertical coverage for the elevation function, the aircraft flew a low-angle 1-degree glide path almost to runway threshold, with a guidance error that still met the full-capability signal quality. This test confirmed that a 1-degree beam-width antenna could provide accurate guidance down to a 1-degree glideslope in the presence of the strong multipath introduced by the airport surface in front of the elevation antenna.

In separate tests, azimuth guidance was measured at "autoland" accuracy 3 feet above the runway. Critical flare guidance was measured as less than ±2.0 feet down to 8 feet above the runway surface over the entire 2500-foot touchdown zone. The 2.0-foot ICAO flare-accuracy specification was obtained over the touchdown zone using an airborne antenna mounted 10 feet above the aircraft wheels. Approach elevation guidance with ±2.0-foot accuracy was measured down to 16 feet over runway threshold.

Operational demonstrations and tests conducted at ten airports thoughout the world, as well as at the NAFEC and Crows Landing test sites, included glideslope approaches from 1-degree to 6-degrees; radial approaches; coupled approaches to evaluate Category I and II operations; lateral and vertical guided curved paths to runway intercept; and automatic landings to simulate Category III conditions. Operations were performed with humped runways, with very large aircraft on nearby taxiways, and in difficult mountain sites.

Two test and demonstration sites—Kristiansand and Brussels—offer examples of some of the problems encountered and resolved by the MLS. Kjevik Airport in Kristiansand, Norway, principally services short-haul flights within Scandanavia. It consists of a single concrete runway about 6200 feet long and 150 feet wide. The runway has a commissioned Category I instrument landing system that provides a 4-degree glide path. The high glide path indicates the obstacle clearance plane required to fly safely over the mountainous terrain that surrounds Kristiansand.

Both the Bendix prototype small-community and basic-narrow-aperture systems were sited on runway 22. Many observers felt that this approach would be unflyable at any glide path with a traditional ILS installation. As a result, the site was considered an attractive choice to demonstrate MLS capabilities. The basic-narrow-aperture system met the ICAO full-capability accuracies down to a 2-degree glide path; the small-community system—with a 2-degree-elevation beam-width—achieved these accuracies down to a 3-degree glide path.

At Brussels National Airport, Belgium, test results showed autoland performance when the test bed system was sited on a long runway (12 000 feet) in the presence of dense airport traffic. The test results in all cases satisfied the ICAO full-capability accuracy specifications. Flight profiles included centerline approaches of 4, 3, and 2 degrees. These profiles were repeated in a diffraction multipath and shadowing experiment.

These flight and operational tests are only part of the evidence supporting the readiness and availability of the TRSB MLS for international standardization. Seven different TRSB systems developed by five different contractors have proved successful in flight tests. Both civilian and military users have successfully used the TRSB format by flying all types of aircraft in manual, coupled approach, and automatic landings. Finally, TRSB ground equipment has been installed without special site preparation at ten different airports, under all climatic conditions and in all geographic environments—and each installation has taken less than a day. ◆

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